UDC 621.316.93
DOI: 10.15587/2312-8372.2017.97507

Trotsenko Ye.,
Brzhezitsky V.,
Masluchenko I.

EFFECT OF PIECEWISE LINEAR CURRENT WAVEFORMS ON SURGE ARRESTER RESIDUAL VOLTAGE

Приведені результати дослідження динамічної моделі нелінійного обмежувача перенапруг. Моделювання виконане за допомогою демонстраційної версії програми Micro-Cap 11. Установлено, що для швидкої оцінки величини залишкової напруги на нелінійному обмежувачі перенапруг можна використовувати кусочно-лінійний опис комутаційних та грозових імпульсів струму без істотної втрати точності результатів.

Ключові слова: *схемотехнічне моделювання, нелінійний обмежувач перенапруг, залишкова напруга, кусочно-лінійна форма.*

1. Introduction

When solving lightning protection problems, various analytic expressions are used to approximate the current in the lightning channel. Undoubtedly, the correct choice of the approximation type of the lightning current waveform in the discharge channel is one of the components of the reliability of obtained results. At the same time, approximations of the lightning current waveform, which do not always accurately describe the actual current in the lightning channel, can give quite acceptable results. As such example can be mentioned a well-known double-exponential pulse, which has been used for many years to approximate both current and voltage waveforms. The double-exponential pulse has a time derivative different from zero value at the initial instant of time. At the same time, it is known from the real oscillograms of lightning currents that the lightning current waveform is characterized by a zero value of the time derivative at the initial instant of time. Nevertheless, the use of a double-exponential pulse gives acceptable results. For example, it was shown in [1] that regardless of whether the current wave has a zero time derivative at the initial instant of time or not, this doesn't affect the residual voltage of the surge arrester. In order for the analytical form of the current to be used in practice, it is first necessary to calculate the amplitude-time parameters of the pulse wave from the given time-to-crest and time-to-half duration of the impulse. For example, the above-mentioned double-exponential wave has three such parameters: a normalizing factor for the wave amplitude and two damping coefficients of the exponents. With the complication of the analytical expression of the lightning current, the definition of its amplitude-time parameters becomes more complicated [2]. When using piecewise linear functions, the problem is much simpler. It is considered that the current wave rises linearly to its maximum value, and then also decays linearly to half its amplitude value. This is undoubtedly a simplification, since it becomes possible to specify pulses with any ratio of time-to-crest and time-to-half duration without complex calculations. It is assumed that the current in the lightning channel can be approximated by a triangular pulse, since the duration of the front is shorter than the tail duration. In particular, triangular pulses are often used in assessing the energy capability of the surge arresters [3]. In connection with this, it is important to study the feasibility of applying piecewise linear current and voltage pulses to estimate the possible values of lightning and switching overvoltage.

2. The object of research and its technological audit

The object of research is the magnitude and shape of the residual voltage that arises between the terminals of the surge arrester models when they are subjected to current and voltage pulses of a piecewise linear waveform. One of the most problematic places in this problem is the approximation of current switching pulses with a short duration and also steep front current pulses. With the help of the well-known double-exponential pulse, it is impossible to describe a pulse which time-to-half duration T_2 is twice bigger the time-to-crest duration T_1. At the same time, switching current pulses in the manufacturer catalogs of the surge arresters have exactly this ratio (30/60 or 45/90 µs). Also the value of the residual voltage at a steep front current pulse with wave shape 1/2 µs and the same ratio are taken place. A rather complex expression was used in [4] to approximate the pulse with the wave shape 45/90 µs. With the help of piecewise linear approximation, it is possible, bypassing complex calculations, to describe pulses of almost any shape, including switching current pulses, steep front current pulses and chopped voltage pulses. In the catalogs of their products, surge arrester manufacturers indicate several values of the residual voltage on the surge arrester at switching and lightning current pulses of different wave shapes and amplitudes. In one or another circuit simulation program, it is possible to determine the residual voltage on the surge arrester at the switching and lightning current pulses of a piecewise linear waveform. The subsequent comparison of these results with the values indicated in the catalog will allow to evaluate the applicability of pulses of this form.

3. The aim and objectives of research

The aim of research is to estimate the error in calculating the residual voltage of surge arrester when using piecewise linear functions to approximate the wave shape of current and voltage waves affecting the surge arresters during lightning strikes.

The following objectives were set to reach this aim:

1. Define residual voltage (and corresponding calculation error) on the surge arrester during the passage of switching, lightning and steep front current pulses of piecewise linear waveform.

2. Compare these results with the values of the residual voltage obtained earlier in paper [4] when used current pulses, approximated by smooth (continuously differentiable) functions.

4. Research of existing solutions of the problem

A review of various analytic expressions for the lightning current pulse in the discharge channel is given in papers [2, 5]. A single common formula for different tasks doesn't exist. To determine the energy capability of the surge arresters, as well as to assess the failure probability of a surge arrester when lightning strikes in papers [3, 6–9] were used current waves that rise and decay linearly. In [10], to determine the voltage at the top of transmission line tower when a direct lightning strike, were also used current waves that rise and decay linearly. In [11], to calculate multiple reflections and refractions of an electromagnetic wave in a branched cable distribution network, was used a similar triangular voltage pulse, increasing and decaying linearly. It is recommended in papers [12, 13] before using the model of surge arrester in realistic power circuits, to test it using triangular, that is, piecewise linear current pulses.

Thus, the results of the analysis allow to conclude that the influence of currents with the piecewise linear waveform on the residual voltage of the surge arresters remains insufficiently studied.

5. Methods of research

To achieve objectives that were set such research method was applied: piecewise linear approximation and circuit simulation on personal computer. The main material in this research is dynamic surge arrester model.

6. Research results

As well as in their previous publications [1, 4], authors continue work on surge arrester modeling by means of the evaluation version of Micro-Cap 11 circuit simulator developed by Spectrum Software Company (United States of America) [14]. The main research circuit is shown in Fig. 1. This circuit corresponds to simplified surge arrester model [15].

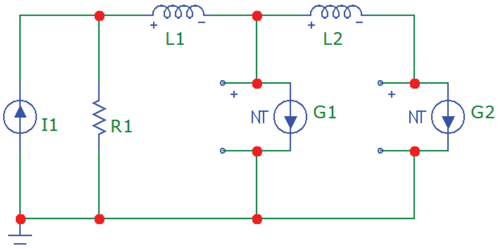


Fig. 1. Surge arrester simulation in Micro-Cap 11 evaluation version using voltage-controlled current sources (NTIofV) G_1 and G_2

In Fig. 1 R_1, L_1 and L_2 – linear, G_1 and G_2 – nonlinear elements of surge arrester model. The procedure of calculation of these parameters is described in [15]. In papers [1, 4] two equivalent ways of metal-oxide surge arrester modeling in the demonstration version of Micro-Cap 11 are presented:

1) with a use of voltage-controlled current sources (NTIofV);

2) with a use of current-controlled voltage sources (NTVofI).

As both ways are equivalent, for research in this work only one of them is chosen. This way use only voltage-controlled current sources (NTIofV). In this work as well as in paper [4] the same model of surge arrester with the rated voltage 108 kV is used. According to [4], inductive parameters of this model are following: $L_1 = 0.947$ μH and $L_2 = 2.842$ μH. The parallel resistor R_1 has a large value – from 1 MΩ [1, 15] to 1000 MΩ [4, 12] and is placed in the circuit to avoid computational troubles. Current source I_1 in Fig. 1 is a table-defined piecewise linear current source.

Fig. 2 shows various switching current pulses with wave shape 45/90 μs and corresponding curves of residual voltage obtained in simulation.

Values of triangular current and voltage sources used in this research are shown in Table 1 (in accordance with Micro-Cap syntax [14]).

Fig. 3 shows various lightning current pulses with the wave shape 8/20 μs and corresponding curves of residual voltage obtained in simulation.

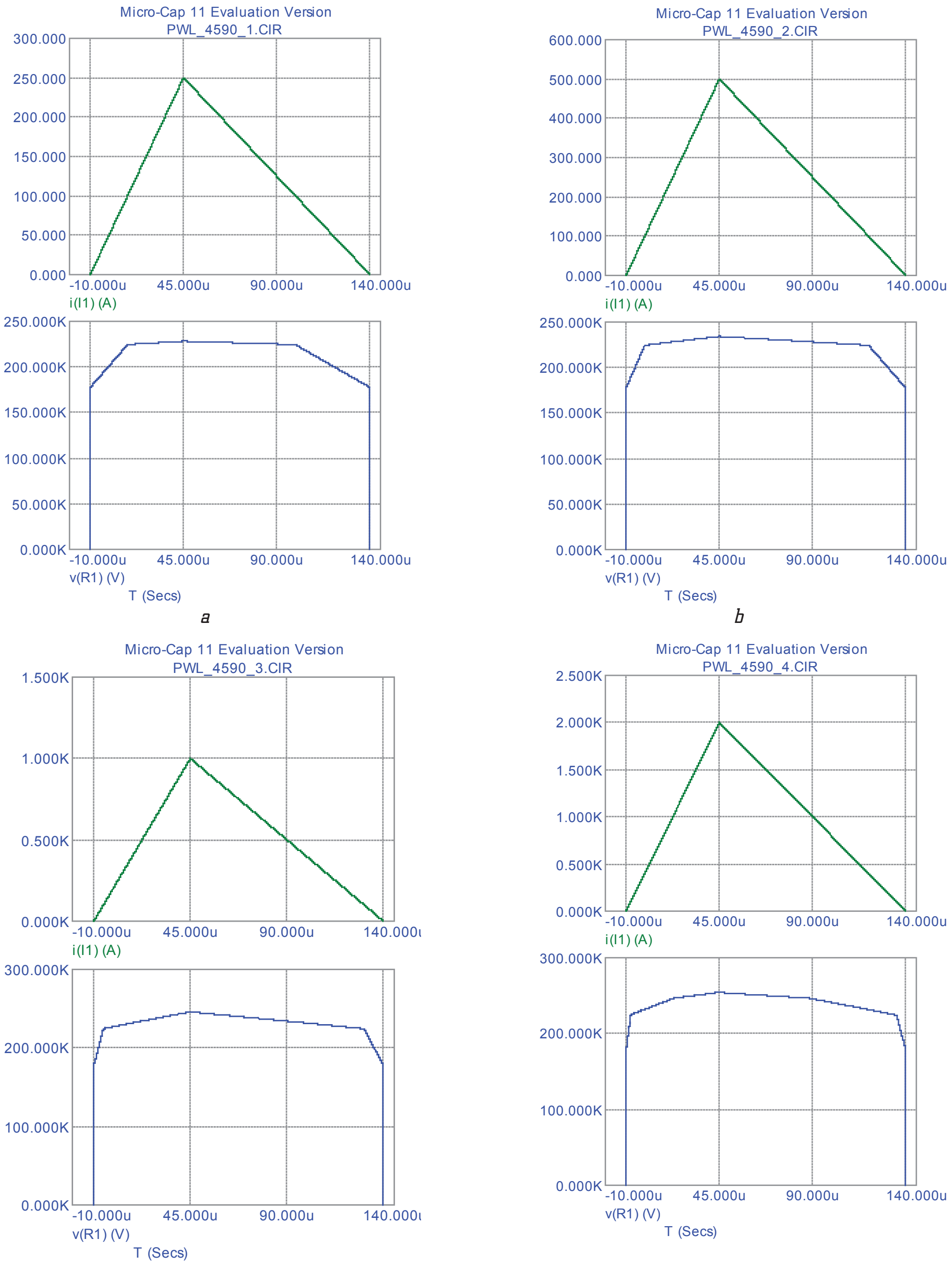
Residual voltage between surge arrester terminals reaches its maximum values at 20 kA lightning current with wave shape 8/20 μs (Fig. 4, *a*) and at 10 kA steep front current with wave shape 1/20 μs (Fig. 4, *b*).

The maximum values of residual voltage curves in Fig. 2–4, at the passage of triangular current pulses through the surge arresters are shown in Table 2. For comparison in Table 2, analogous values taken from paper [4] are shown in brackets, but at use of smooth (continuously differentiated) functions for the discharge current approximation. Simulation relative error in Table 1, 2 was determined using the following formula:

$$\xi = \frac{V'_{rT_1/T_2} - V_{rT_1/T_2}}{V_{rT_1/T_2}} \cdot 100\,\%, \qquad (1)$$

where V'_{rT_1/T_2} – residual voltage value at the passage of current pulse with the wave shape T_1/T_2 μs through the surge arrester, received in simulation; V_{rT_1/T_2} – corresponding value taken from the catalog of surge arresters.

As can be seen from Table 2, the simplification of discharge current waveform has no significant effect on relative calculation error of residual voltage of surge arrester. Time-to-crest duration and current amplitude, but not time-to-half duration, has main effect on the value of residual voltage of surge arrester. Therefore, if it is necessary to estimate only maximum value of residual voltage, it is possible to use impulse of current which will look like an isosceles triangle [12, 13]. Such pulse has rise time to maximum value equal to fall time to zero value and accordingly equal to pulse front duration. This feature is shown in Fig. 5.



a *b*

c *d*

Fig. 2. Residual voltage (at the bottom) at various switching current pulses (at the top) with wave shape 45/90 μs and different amplitude passing through the surge arrester: *a* – 0.25 kA; *b* – 0.50 kA; *c* – 1.0 kA; *d* – 2.0 kA

Table 1

Triangular pulses in the research

No.	Pulse (amplitude, wave shape)	Source value in Micro-Cap 11 evaluation version
Current pulses (for source in Fig. 1)		
1	0.25 kA, 45/90 μs	DC 0 AC 1 0 PWL 0, 0, 45e-6, 0.25e3, 1.35e-4, 0
2	0.5 kA, 45/90 μs	DC 0 AC 1 0 PWL 0, 0, 45e-6, 0.50e3, 1.35e-4, 0
3	1.0 kA, 45/90 μs	DC 0 AC 1 0 PWL 0, 0, 45e-6, 1.0e3, 1.35e-4, 0
4	2.0 kA, 45/90 μs	DC 0 AC 1 0 PWL 0, 0, 45e-6, 2.0e3, 1.35e-4, 0
5	1.5 kA, 8/20 μs	DC 0 AC 1 0 PWL 0, 0, 8e-6, 1.5e3, 3.2e-5, 0
6	3.0 kA, 8/20 μs	DC 0 AC 1 0 PWL 0, 0, 8e-6, 3.0e3, 3.2e-5, 0
7	5.0 kA, 8/20 μs	DC 0 AC 1 0 PWL 0, 0, 8e-6, 5.0e3, 3.2e-5, 0
8	10.0 kA, 8/20 μs	DC 0 AC 1 0 PWL 0, 0, 8e-6, 10.0e3, 3.2e-5, 0
9	20.0 kA, 8/20 μs	DC 0 AC 1 0 PWL 0, 0, 8e-6, 20.0e3, 3.2e-5, 0
10	10.0 kA, 1/20 μs	DC 0 AC 1 0 PWL 0, 0, 1e-6, 10e3, 3.9e-5, 0
Voltage pulse (for source in Fig. 6)		
11	400.0 kV, 1.2/50 μs	DC 0 AC 1 0 PWL 0, 0, 1.2e-6, 400e3, 9.88e-5, 0

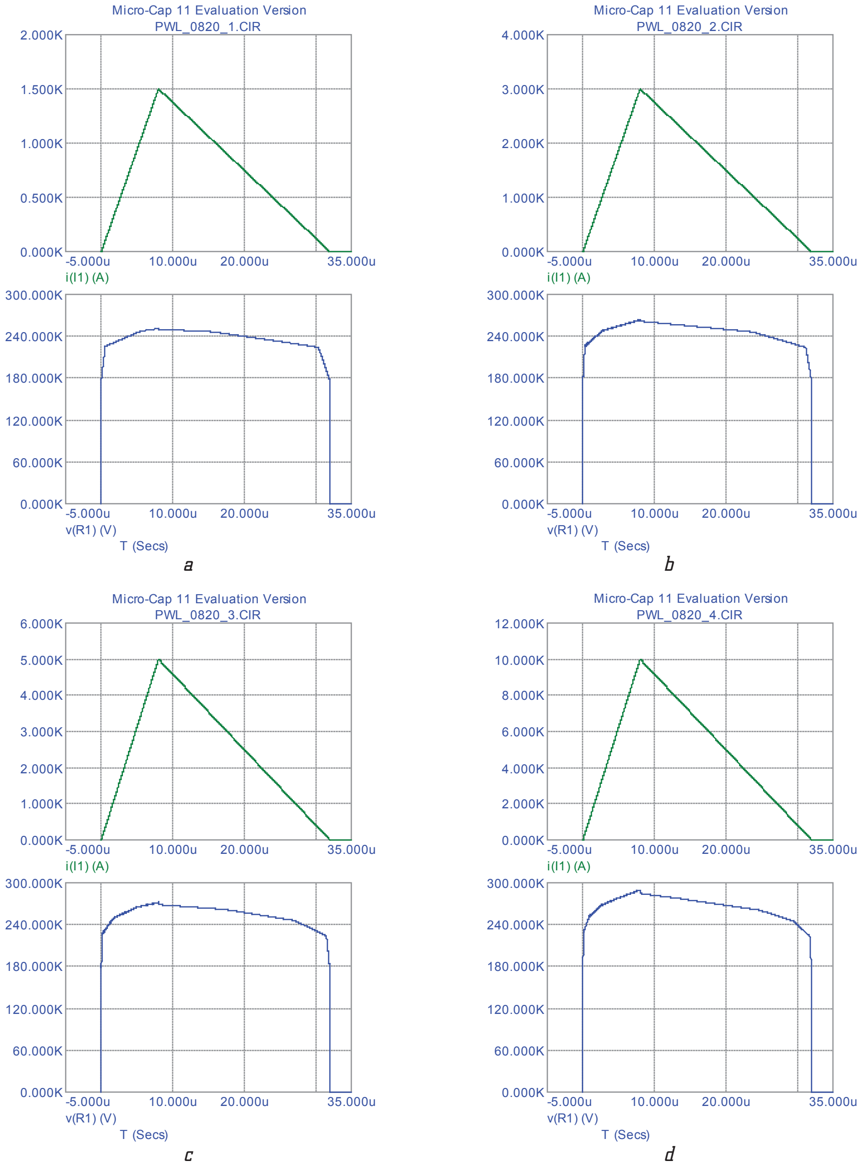


Fig. 3. Residual voltage (at the bottom) at various lightning current pulses (at the top) with wave shape 8/20 μs and different amplitude passing through the surge arrester: *a* – 1.5 kA; *b* – 3.0 kA; *c* – 5.0 kA; *d* – 10.0 kA

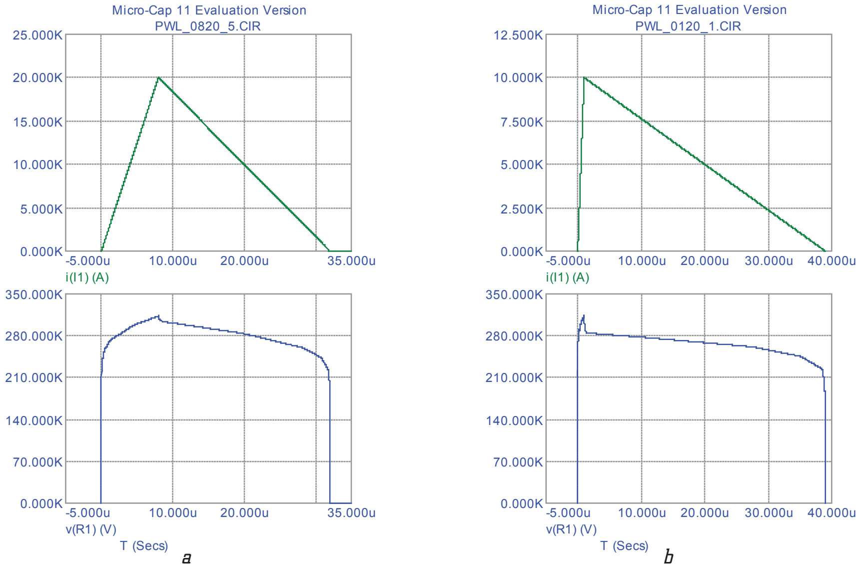
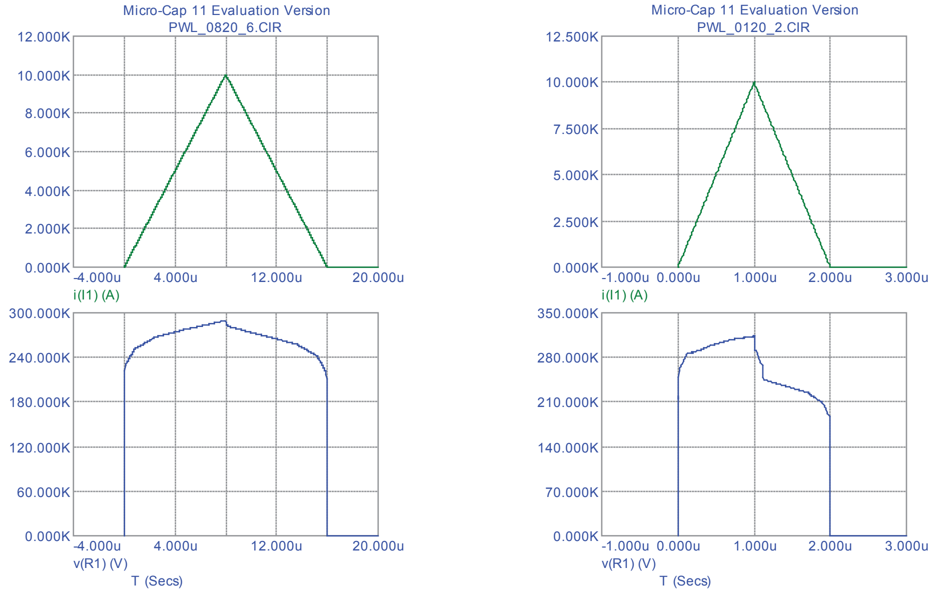


Fig. 4. Residual voltage (at the bottom) at various current pulses (at the top) passing through the surge arrester: *a* – 20.0 kA lightning current with wave shape 8/20 μs; *b* – 10.0 kA steep front current with wave shape 1/20 μs

Table 2

Residual voltage of surge arrester at various current pulses (analogous values taken from paper [4] are shown in brackets)

No.	Current pulse (amplitude, wave shape)	Maximum residual voltage, kV		Relative error, %
		catalog	simulation	
1	0.25 kA, 45/90 μs	206.0	228.30 (228.29)	+10.83 (+10.82)
2	0.5 kA, 45/90 μs	214.0	234.31 (234.29)	+9.49 (+9.48)
3	1.0 kA, 45/90 μs	223.0	246.08 (246.02)	+10.35 (+10.32)
4	2.0 kA, 45/90 μs	236.0	254.55 (254.39)	+7.86 (+7.79)
5	1.5 kA, 8/20 μs	241.0	251.16 (250.56)	+4.22 (+3.97)
6	3.0 kA, 8/20 μs	254.0	263.69 (262.45)	+3.81 (+3.33)
7	5.0 kA, 8/20 μs	263.0	272.02 (269.78)	+3.43 (+2.58)
8	10.0 kA, 8/20 μs	285.0	290.01 (286.33)	+1.76 (+0.47)
9	20.0 kA, 8/20 μs	316.0	313.25 (307.69)	–0.87 (–2.63)
10	10.0 kA, 1/20 μs	315.0	313.51 (319.11)	–0.47 (+1.30)



a *b*

Fig. 5. Residual voltage (at the bottom) at isosceles triangle current pulses (at the top) passing through the surge arrester: *a* – 10.0 kA current with wave shape 8/12 μs; *b* – 10.0 kA current with wave shape 1/1.5 μs

The maximum value of residual voltage at the lightning pulse 10.0 kA, 8/20 μs (triangle, Fig. 3, *d*) is 290.01 kV. At the simplified pulse 10.0 kA, 8/12 μs (isosceles triangle, Fig. 5, *a*) is obtained almost the same value 289.92 kV. Analogously at the steep front current pulse 10.0 kA, 1/20 μs (triangle, Fig. 4, *b*) the maximum value is equal to 313.51 kV. At the simplified pulse 10.0 kA, 1/1.5 μs (isosceles triangle, Fig. 5, *b*) we again obtain almost the same value, equal to 313.42 kV.

The subject of the further research is process of overvoltage suppression by surge arresters. The simplified circuit for determining of residual (limited) voltage of surge arrester when surge wave comes is shown in Fig. 6.

In Fig. 6 R_2 – resistor representing a surge impedance of an overhead transmission line (it is accepted an equal to 300 Ω); V_1 – piecewise linear waveform voltage source (400.0 kV amplitude and wave shape 1.2/50 μs). The curves obtained in simulation, are shown in Fig. 7.

As can be seen from Fig. 7, the surge arrester reduces the peak value of transient overvoltage from 400.0 kV to 238.77 kV. The peak voltage drop across the resistor representing surge impedance is 161.23 kV.

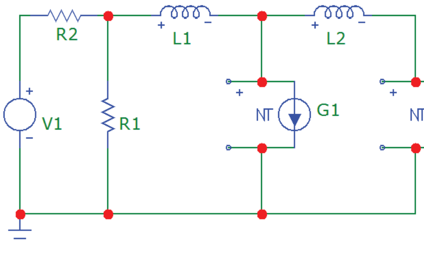
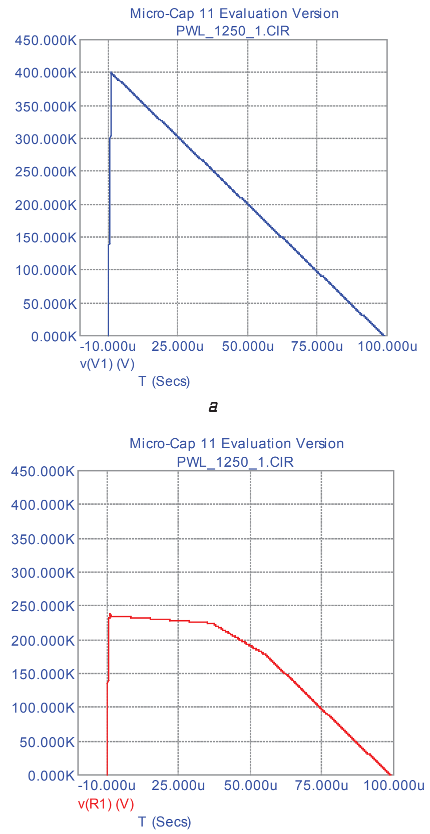


Fig. 6. Simulation of overvoltage suppression by surge arrester in Micro-Cap 11 evaluation version



a

b

Fig. 7. Overvoltage wave passing through the surge arrester: *a* – incoming wave 400.0 kV, 1.2/50 µs; *b* – residual (limited) voltage between surge arrester terminals

7. SWOT analysis of research results

Strengths. The strengths of the proposed approach are:
– reduction of time wasted by the user to calculate the amplitude-time parameters of the given current pulse. It is also shown that simplification of the approximation of the discharge current wave has no significant effect on obtained value of surge arrester residual voltage;
– increase in speed of computation on personal computer. Circuit simulation software process circuits with simple waveform current and voltage sources faster.

Weaknesses. The weaknesses of the proposed approach are:
– used functions differ from the real oscillograms of lightning currents, characterized by a zero value of the time derivative at the initial instant of time;
– simulation was performed in demonstration version of Micro-Cap circuit simulator. In the professional version there is no limitation on the maximum number of elements in the circuit, and computations are performed faster.

Opportunities. The additional possibilities of proposed approach are:
– simple determination of current and voltage single pulses with any amplitude and wave shape. For example, pulses 1/2 µs, 4/10 µs, 2/70 µs, 30/60 µs, 10/350 µs and others, which are used in practice of lightning protection;
– modeling the lightning current consisting of several consecutive impulses with the help of only one current source in the circuit.

Threats. The proposed approach should not be used for computation of overvoltage in complex branched electrical networks. The proposed approach is positioned only as auxiliary method rather than the main method of computation. Nevertheless, to use this method it is required the employee knowing both the theory of linear and nonlinear electric circuits and circuit simulation skills.

8. Conclusions

1. By means of evaluation version of Micro-Cap 11 circuit simulator the residual voltage on the surge arrester terminals is computed during a passage of the current pulses with different amplitude and wave shape. Current sources used in this research represent sources of simplified triangular current pulses.

2. These obtained values of residual voltage were compared with simulation results obtained earlier with a use of current pulses, approximated by smooth (continuously differentiable) functions. Comparison of the results suggests that proposed simplification of discharge current waveform has no significant effect on relative calculation error of residual voltage on surge arrester.

References

1. Trotsenko, Ye. Surge arrester modeling using Micro-Cap [Text] / Ye. Trotsenko, V. Brzhezitsky, I. Masluchenko // Technology Audit and Production Reserves. – 2016. – № 6/1 (32). – P. 26–30. doi:10.15587/2312-8372.2016.86137
2. Heidler, F. Calculation of lightning current parameters [Text] / F. Heidler, J. M. Cvetic, B. V. Stanic // IEEE Transactions on Power Delivery. – 1999. – Vol. 14, № 2. – P. 399–404. doi:10.1109/61.754080
3. Garcia-Gracia, M. Evaluation of the failure probability for gapless metal oxide arresters [Text] / M. Garcia-Gracia, S. Baldovinos, M. Sanz, L. Montanes // 1999 IEEE Transmission and Distribution Conference (Cat. No. 99CH36333). – 1999. – Vol. 2. – P. 700–705. doi:10.1109/tdc.1999.756136
4. Trotsenko, Ye. Study of surge arrester model under influence of various current pulses [Text] / Ye. Trotsenko, V. Brzhezitsky, I. Masluchenko // Technology Audit and Production Reserves. – 2017. – № 1/1 (33). – P. 44–48. doi:10.15587/2312-8372.2017.92244
5. Gamerota, W. R. Current waveforms for lightning simulation [Text] / W. R. Gamerota, J. O. Elisme, M. A. Uman, V. A. Rakov // IEEE Transactions on Electromagnetic Compatibility. – 2012. – Vol. 54, № 4. – P. 880–888. doi:10.1109/temc.2011.2176131
6. Nakada, K. Energy absorption of surge arresters on power distribution lines due to direct lightning strokes-effects of an overhead ground wire and installation position of surge arresters [Text] / K. Nakada, T. Yokota, S. Yokoyama, A. Asakawa, M. Nakamura, H. Taniguchi, A. Hashimoto // IEEE Transactions on Power Delivery. – 1997. – Vol. 12, № 4. – P. 1779–1785. doi:10.1109/61.634205
7. Nakada, K. Analytical study on prevention methods for distribution arrester outages caused by winter lightning [Text] / K. Nakada, S. Yokoyama, T. Yokota, A. Asakawa, T. Kawabata // IEEE Transactions on power delivery. – 1998. – Vol. 13, № 4. – P. 1399–1404. doi:10.1109/61.714514
8. Hassan, N. H. N. Analysis of arrester energy for 132 kV overhead transmission line due to back flashover and shielding failure [Text] / N. H. N. Hassan, A. H. A. Bakar, H. Mokhlis, H. A. Illias // 2012 IEEE International conference on power and energy (PECon). – 2012. – P. 683–688. doi:10.1109/pecon.2012.6450302
9. Annamalai, A. Sizing of surge arresters for 400 kV substation – A case study [Text] / A. Annamalai, A. Gulati, R. Koul // 2011 International Conference on Emerging Trends in Electrical and Computer Technology. – 2011. – P. 206–211. doi:10.1109/icetect.2011.5760117

10. Lantharthong, T. Effect of waveform and impulse resistance on lightning performance in distribution system [Text] / T. Lantharthong, N. Rugthaicharoencheep, K. Supanus, A. Phayomhom // 2014 International Conference on Lightning Protection (ICLP). – 2014. – P. 1766–1769. doi:10.1109/iclp.2014.6973415
11. Hu, H. Modeling of lightning surge protection in branched cable distribution network [Text] / H. Hu, M. S. Mashikian // IEEE Transactions on Power Delivery. – 1990. – Vol. 5, № 2. – P. 846–853. doi:10.1109/61.53092
12. Durbak, D. W. Surge arrester modeling [Text] / D. W. Durbak // 2001 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No. 01CH37194). – 2001. – P. 728–730. doi:10.1109/pesw.2001.916946
13. Martinez, J. A. Parameter Determination for Modeling Systems Transients – Part V: Surge Arresters [Text] / J. A. Martinez, D. W. Durbak // IEEE Transactions on Power Delivery. – 2005. – Vol. 20, № 3. – P. 2073–2078. doi:10.1109/tpwrd.2005.848771
14. Micro-Cap 11. Electronic Circuit Analysis Program. Reference Manual [Electronic resource]. – Ed. 11. – Sunnyvale, CA: Spectrum Software, 2014. – 1040 p. – Available at: \www/URL: http://www.spectrum-soft.com/down/rm11.pdf
15. Pinceti, P. A simplified model for zinc oxide surge arresters [Text] / P. Pinceti, M. Giannettoni // IEEE Transactions on Power Delivery. – 1999. – Vol. 14, № 2. – P. 393–398. doi:10.1109/61.754079

ВЛИЯНИЕ ТОКОВ КУСОЧНО-ЛИНЕЙНОЙ ФОРМЫ НА ОСТАЮЩЕЕСЯ НАПРЯЖЕНИЕ НЕЛИНЕЙНОГО ОГРАНИЧИТЕЛЯ ПЕРЕНАПРЯЖЕНИЙ

Приведены результаты исследования динамической модели нелинейного ограничителя перенапряжений. Моделирование выполнено с помощью демонстрационной версии программы Micro-Cap 11. Установлено, что для быстрой оценки величины остающегося напряжения на нелинейном ограничителе перенапряжений можно использовать кусочно-линейное описание коммутационных и грозовых импульсов тока без существенной потери точности результатов.

Ключевые слова: схемотехническое моделирование, нелинейный ограничитель перенапряжений, остающееся напряжение, кусочно-линейная форма.

Trotsenko Yevgeniy, *PhD, Associate Professor, Department of High Voltage Engineering and Electrophysics, National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Ukraine, e-mail: y.trotsenko@kpi.ua, ORCID: http://orcid.org/0000-0001-9379-0061*

Brzhezitsky Volodymyr, *Doctor of Technical Sciences, Professor, Department of High Voltage Engineering and Electrophysics, National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Ukraine, e-mail: v.brzhezitsky@kpi.ua, ORCID: http://orcid.org/0000-0002-9768-7544*

Masluchenko Igor, *PhD, Associate Professor, Department of High Voltage Engineering and Electrophysics, National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Ukraine, e-mail: i.masluchenko@kpi.ua, ORCID: http://orcid.org/0000-0001-6073-9649*

UDC 621.314.5:681.5:621.313.3
DOI: 10.15587/2312-8372.2017.99929

Kulagin D.,
Yatsenko D.

INVESTIGATION OF PECULIARITIES OF DECOMPOSITION OF TRACTION ELECTRIC DRIVES OF MOBILE ELECTROTECHNICAL COMPLEXES

Досліджено особливості проведення декомпозиції систем тягових електроприводів для різних видів та конструкцій рухомих електротехнічних комплексів. Проведено аналіз практичного досвіду декомпозиції систем тягових електроприводів та узагальнення методики визначення структури та параметрів при заданих вимогах з боку рухомого електротехнічного комплексу. Запропоновано метод підвищення енергоефективності дизель-генераторної електромеханічної системи транспортного засобу за статичними та динамічними характеристиками.

Ключові слова: *декомпозиція електроприводу, електротехнічний комплекс, тяговий привод, автономна система, дизель-генераторна система.*

1. Introduction

A significant amount of work has been devoted to improving the individual elements of the diesel-generator electromechanical system. For example, in [1–4] the mutual influence of separate groups of elements of common industrial electric drives, in particular the redactor-traction motor, the traction motor-reducer on the general potential of energy efficiency according to static characteristics is shown. However, electric drives of vehicles are more complex in structure, contain a larger number of groups of interconnected elements. So they can have a greater energy potential in the case of a mutual influence between groups of these elements with static characteristics.

Solving the problem of increasing the energy potential of an electromechanical system is possible only in a complex manner. At the same time, it is necessary to consider the established mode of operation of the entire system as a whole, taking into account the conditions for the rational operation of its individual components, provided that the relationship between them is taken into account. After all, a fairly frequent practical situation is when a rational operating mode of individual elements of an electromechanical system and optimal control of